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# HDR PHASE II VIBRATIONAL EXPERIMENTS*

L. Malcher, HDR Project
Kernforschungszentrum Karlsruhe, FRG

C. A. Kot
Argonne National Laboratory
Argonne, Illinois, U.S.A.

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## Abstract

As part of the second phase of vibrational/earthquake investigations at the HDR (Heissdampfreaktor) Test Facility in Kahl/Main, FRG, high-level shaker tests (SHAG) were performed during June and July 1986. The purpose of these experiments is to investigate full-scale structural response, soil-structure interaction, and piping and equipment response under strong excitation conditions. While global safety considerations imposed load limitations, the HDR soil/structure system was nevertheless tested to its capacity limits. The performance of up to seven different multiple support pipe hanger configurations (ranging from flexible to stiff systems) was evaluated in the tests. Data obtained in the tests serve to validate analysis methods.

## 1. Introduction

The HDR (Heissdampfreaktor) Test Facility (see Fig. 1) in Kahl/Main, FRG, has since 1975 been used to perform vibrational, thermal hydraulic, blowdown and other experiments related to the design and safety of nuclear power plants. During the first phase of the HDR Program of testing (PHDR), the HDR building and equipment were subjected to many low and medium level mechanical excitations (shaker, buried explosives, snapback). In the second phase of vibrational/earthquake investigations the HDR system is being tested at high level of excitation. The centerpiece of these investigations is the high level shaker tests (SHAG) which were performed at the HDR in June and July 1986. Their purpose was to investigate full-scale structural response, soil-structure interaction, and piping and equipment response under strong excitation conditions, i.e., under excitation levels that will induce significant strains in the structure and soil and produce nonlinear effects in

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the soil-structure system and piping. As with all HDR experiments, the primary intent is to use the SHAG tests to verify/validate calculational procedures and analysis methods. At the same time the experimental data provide direct information on the response and performance of structural systems, piping and equipment under high dynamic loading, which may have direct applicability to understanding the behavior of nuclear power plant systems.

The SHAG experiments were performed as part of the HDR Safety Project (PHDR) conducted by the Kernsforschungszentrum Karlsruhe (KfK), and were supported by the Government of the Federal Republic of Germany (FRG) and the U.S. Nuclear Regulatory Commission, Office of Research (NRC/RES). The latter involvement is part of a program on the validation of seismic calculational methods conducted by the Argonne National Laboratory (ANL) for NRC/RES. Additional participation in the SHAG experiments included the Electric Power Research Institute (EPRI), the Idaho National Engineering Laboratory (INEL), and German as well as U.S. industry.

## 2. Shaker Design and Operation

The shaker used in the SHAG experiments is a very large eccentric-mass coast-down shaker designed by ANCO Engineers, Inc., of Culver City, CA (Ref. 1). Most of the design and functional calculations of the shaker's dynamic behavior were performed by the Fraunhofer Institut für Betriebsfestigkeit (LBF), Darmstadt, FRG (Ref. 2). Safety calculations for the shaker, its mounting and the HDR soil-structure system were performed by the Engineering Firms of Zerna-Schnellenbach in Bochum, FRG (Ref. 3) and Hochtief AG in Frankfurt, FRG (Ref. 4).

The masses of each of the two shaker arms (which form the eccentricity) are made up of an assembly of steel plates mounted on the arm base-plate, and can be varied up to a total of 40 tons each. The shaker is capable of developing in excess of 1000 tons of force. It is mounted in a very stiff frame on the operating floor of the HDR building (see Fig. 2) to provide strong excitation to the entire HDR soil/structure/equipment system. The shaker was designed to develop maximum accelerations of the HDR building of the order of 5 $m/s^2$ and maximum displacement of about ± 7 cm. The total eccentricity of the shaker was designed to vary between 4000 and 145,000 kgm. In operation the shaker is brought up to the desired starting speed (1.2 - 8.0 Hz) with the two arms in a balanced condition. One of its arms is permanently fixed to the drive shaft, while the other movable arm is hinged to the shaft by a slightly eccentric support. In the balanced condition the movable arm is fixed by an explosive bolt. After the desired starting speed is reached the shaker arms are uncoupled from the drive system. Firing the explosive bolt releases the movable arm, which swings around and couples with the fixed arm, forming a large eccentric mass that provides a variable (both in magnitude and direction) force during coast-down. As the shaker coasts down through the fundamental frequencies of the HDR soil-structure system strong resonances occur. During the entire shaker run there is strong coupling and feedback between HDR response and shaker forcing, thus a nonlinear coupled system results. Details of shaker design and operation were discussed in the previous Water Reactor Safety Research (WRSR) Information Meeting (Ref. 5) and the actual shaker is shown in Fig. 3.

Preliminary tests were conducted in February 1986 to check out the functionality of the shaker. Five tests were planned, 3 with the shaker arms balanced (no loads on the HDR building) and 2 with the shaker arms unbalanced providing excitation to the building. The latter tests were completely successful proving the design concept and operation of the shaker. However, in the experiments with the balanced arms it was not possible to reach the desired shaker frequencies because the air resistance was much higher than expected and the maximum torque that can be generated by the drive system was limited. Thus, the maximum frequency reached with no plates on the shaker arms was 5.25 Hz rather than the desired 8.0 Hz. This problem was subsequently overcome by providing an enclosure for the shaker (see Fig. 4) which substantially lowered the aerodynamic drag. It was also found that the eccentricity of the bare arms of the shaker was substantially higher at 5700 kgm than the estimated value of 4000 kgm. Since this would have generated forces much higher than intended during the 8.0 Hz tests, the mass of the arms was reduced by cutting out part of the base plates. This reduced the eccentricity of the bare arms of the shaker to about 4,700 kgm. Just prior to the start of the actual SHAG experiments, the functionality of the shaker was again tested and all systems performed as expected.

## 3. SHAG Experiments

As stated earlier the purpose of the SHAG tests was to investigate full scale structure/soil, equipment and piping response under strong vibrational excitation and to validate predictive analyses. While the interests of PHDR and NRC/RES includes all aspects of the SHAG testing, most other participants focus primarily on the behavior of piping systems. In particular the response of the VKL (Versuchskreislauf) piping system with different multiple support (hanger) configurations was of interest to all participants.

The VKL piping (see Fig. 5) consists of a number of pipe runs ranging in nominal size from 100 mm to 250 mm. It is attached to the HDU vessel and associated manifolds and forms part of the experimental piping system at the HDR. The top of the pipe runs at about 28 m above ground level, just under the HDR operating floor (where the shaker is located). The original German hanger system provided primarily vertical dead weight support and consisted of 11 spring and constant force hangers and one threaded rod. The orignal intention was to compare in the SHAG tests the performance of this very flexible conventional support system with a typical U.S. stiff support system containing snubbers and struts. Also as part of the NRC/RES Equipment Qualification Research Program, the INEL intended to evaluate the performance of a typical U.S. gate valve during SHAG testing. Thus, such an 8" valve was incorporated into the VKL piping system (see Fig. 6). INEL then designed a typical U.S. hanger system adding six snubbers (see Fig. 7) and six rigid struts to the VKL hanger system and replacing one of the German spring hangers with a much higher rated hanger of the same type to accommodate the added weight of the valve as shown in Fig. 5.

EPRI and its industry associates intended to evaluate two additional hanger configurations. The first of these, designed by Bechtel Corporation, are energy absorber supports which damp out the motion of the piping through the plastic deformation of an assembly of steel plates incorporated into the support. The other configuration uses seismic stops, designed by R. L. Cloud and Associates, which replace the snubbers. This system allows free motion until a certain displacement is reached, at which the pipe impacts the stops limiting further movement in the given direction. As part of German industry contribution to the SHAG experiments, Kraftwerk Union (KWU), Offenbach, FRG, designed a hanger system for the VKL piping which in addition to the dead weight supports uses only 5 rigid struts placed such as to prevent large dynamic motions of the piping. All the alternative hanger designs of the VKL were motivated by the desire to replace snubbers which have proved troublesome in nuclear power plants. Therefore, the objective of these experiments was to compare and evaluate the behavior of the VKL piping system with the different support systems under identical loading conditions.

### 3.1 Test Plans

In early March 1986 a meeting was held at the HDR Test Facility in Kahl/Main, FRG, to plan the SHAG test matrix and sequence. A total test period of 6 weeks was foreseen starting on 2 June 1986 and continuing through 11 July 1986. It was intended to test all five hanger configurations described above. All but two tests were designed to generate nominally the same peak force of $10^4$ kN, starting with different shaker frequencies. Higher shaker frequencies (8,0, 5.6 Hz) were intended primarily for piping excitation while the lower frequencies (1.6, 2.1, 3.1 Hz) were primarily intended to challenge the soil-structure system.

Results of safety calculations (Ref. 3) and of the functionality tests indicated that some of the test runs would be a severe challenge to the HDR building. In particular the 1.6 Hz runs were expected to strongly excite the rocking mode (nominally at 1.4 Hz) and the 3.1 Hz tests would strongly excite the out-of-phase bending mode at 2.5 Hz. In both cases it was thought that the foundation slab of the HDR would be severely challenged. Also loads in the embedded portion of the outer shield building walls would be high. Thus, in the resulting test matrix (Fig. 8) the test runs which would challenge the HDR structure were placed at the end of the test sequence. Four groups, of five tests each, were to compare the response of the VKL piping system with the different hanger configurations. Two of these test sequences (at 5.6 and 8.0 Hz) were to be run in hot conditions (210°C), this would permit the evaluation of piping response under both hot and cold conditions. Secondly under hot conditions it is possible to pressurize the VKL to 70 bars and thus better evaluate the performance of the gate valve under combined vibrational excitation and hydrodynamic loading.

Over 330 channels of instrumentation was planned by the HDR Central Measurement Facility (ZMA), with acceleration and strain being the primary measurements of structure and equipment response. All essential parts of the facility were instrumented, e.g., accelerations of the HDR building (structure) and ground accelerations in two orthogonal radial directions and at two depths were measured. Also all piping systems of interest were instrumented as were major components and vessels. Strain measurements in the HDR walls, foundation slab, piping and vessels were provided. Some of these measurements were intended as safety checks as were some of the measurements of acceleration and velocity at the VAK (Versuchsatomkraftwerk) installation. The latter is a recently decommissioned experimental power reactor which shares the same site with the HDR and is located at a distance of about 100 m from the HDR (see Ref. 6).

The HDR instrumentation was supplemented by more than 100 channels concentrated on the VKL piping system and the 8" U.S. Gate Valve. This instrumentation was provided by INEL under the sponsorship of primarily NRC/RES with additional support from EPRI. Again, accelerometers predominated, with some displacement, force and strain measurements. Specifically, acceleration of the HDR walls at the points of VKL piping support attachment were measured (see Fig. 9). These measurements are intended to serve as input to post-test piping analysis calculations. Also the detailed response of the piping was measured as were all operating parameters of the valve.

### 3.2 Test Performance

As planned the actual main series of SHAG tests commenced on 2 June 1986, with Test No. 34 which was run with the minimum available eccentricity of 4700 kgm at 6 Hz starting frequency. While the peak forces, accelerations and displacements were close to values predicted by LBF (Ref. 2), the duration of the shaker coast-down was much longer (~ 100 s) than predicted (40 s). The reason for this is the use of the enclosure around the shaker. Its effect is to reduce aerodynamic drag both during shaker spin-up and coast-down. Because of the long test duration more energy is radiated to the surrounding soil causing stronger than expected vibrational effects at some distance from the HDR, e.g., at the VAK installation. While the measured accelerations at the VAK were at least an order of magnitude lower than deemed acceptable, the experiment led to protests from the VAK management.

With the agreement of all major participants two additional pipe support configurations for the VKL were added to the test matrix. One test each was planned for viscous damper supports of GERB, Berlin, Germany, and for modified viscous dampers designed by ANCO Engineers. Two of the former were used while six of the latter replaced all snubbers in the U.S. NRC system.

Additional safety calculations by Hochtief AG (Ref. 4) as well as a "best estimate" soil-structure interaction calculation and detailed stress analyses performed by Weidlinger Associates, Palo Alto, CA (Ref. 7) indicated, that the 1.6, 2.1 and 3.1 Hz tests when run at full load ($10^4$ kN) would provide an even more severe than anticipated challenge to the HDR structure. Reexamination of the structural drawings also indicated lower capacity in the embedded region of the walls of the shield building. This led to a reordering of the test sequence, with the high frequency tests for the piping being advanced in the schedule. Thus, while the first week of testing proceeded essentially as planned, in the second week of testing 8.0 Hz experiments with three different pipe hanger configurations were performed with the piping in cold conditions.

A test delay occurred at the end of the first week after Test 37 (at 2.1 Hz and less than half of full load) resulted in considerable shifting in a section of the outer shield wall around the equipment hatch made up of concrete blocks. The concrete blocks had to be secured by a steel structure. Other delays came about because of interference from the VAK management and protests of antinuclear intervenors. All these problems necessitated the reevaluation, inspection and reapproval for further testing by the Technical Evaluation Agency (TÜV) and the Licensing Agency of the

Bavarian State Ministry. Hence, no tests were performed during the third week.

At the same time the concern for the global integrity of the HDR structure necessitated a detailed evaluation of crucial test data (accelerations, displacements and strains) after each test. These measurements were compared with predictions and estimates of structural capacity to guide the progress of experiments. All these factors caused an overall extension of the test period to nearly 8 weeks. The tests actually performed and their sequence are listed in Fig. 10. As indicated only the 8.0, 5.6 and 6.0 Hz tests were performed at or near full load ($10^4$ kN); all other tests were performed at reduced loads. Only the 4.5 Hz runs were performed with hot conditions in the piping system. All tests at 3.1 Hz and 2.1 Hz (at full load) were dropped to avoid challenging the walls of the outer shield building which experience their most severe strains in the out-of-phase bending mode. The 1.6 Hz tests, which involve the rocking mode, were limited to a maximum of about two-thirds of full load. A comparison of the planned and actual force-frequency region for the SHAG tests is shown in Fig. 11. All testing was completed on 22 July 1986. Detailed measurements of the response of the VKL piping and the performance of the 8" Gate Valve were carried during nearly all experiments, the exception being the 1.6 Hz tests conducted last in the sequence (see Fig. 10).

Ambient response measurement tests (RAU) were carried out prior to, during, and after the performance of the SHAG experiments. The RAU tests provide a measure of the changes in dynamic characteristics which occur in the HDR soil/structure system due to high level excitation produced by the SHAG testing. The combined SHAG and RAU results will allow the investigation of nonlinear effects.

## 4. Discussion

Pretest and blind post-test calculational predictions are performed by a number of organizations for many aspects of the SHAG tests. To allow for an orderly completion of the post-test calculations all experimental data are held secure and will not be released until these calculations are completed.

It is currently anticipated that at least the building response and soil/structure interaction data will be released in December 1986. The calculational efforts completed or in progress include predictions of the soil-structure interaction, building response including stress analyses, and piping response. The latter are carried out in the blind post-test mode and use measured building response as input.

The SHAG tests were planned to provide the maximum possible loading for the HDR soil/structure system and the piping without inducing global structure/soil failure which would endanger the integrity of the containment. As indicated above safety considerations for the HDR building necessitated some curtailment of the test plans (Fig. 11). In particular, the test runs which strongly excite the main structural modes (out-of-phase bending nominally at 2.5 Hz and rocking nominally at 1.4 Hz) had to be reduced in load or abandoned. The major reason for this is the weakness of the outer concrete HDR shield building, whose cylindrical walls have very little reinforcement in the embedded region and which could thus fail in tension during bending.

In spite of the limitations imposed on the testing the overall goals of the SHAG tests were accomplished. Peak accelerations and displacements in the HDR building were quite substantial and nonlinear behavior of the soil-structure system was clearly observed. Much local damage, such as concrete cracking and interior masonry wall collapse occurred. Substantial amounts of energy were transferred to the surrounding soil, particularly during experiments challenging the rocking mode (1.6 Hz runs). This is evidenced by the high accelerations measured in the soil, cracking of soil (circumferential) away from the building, separation at the soil/structure interface, and soil subsidence. Impact occurred between the HDR building and the equipment tower as well as the connecting bridge to the Office Building. Strains in the HDR shield building walls approached or exceeded their estimated limit values. Finally, accelerations and motions of the VKL piping measured in the SHAG tests are comparable with values expected during strong motion earthquakes.

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Fig. 1. Aerial View of HDR (left) and VAK (right) Facilities

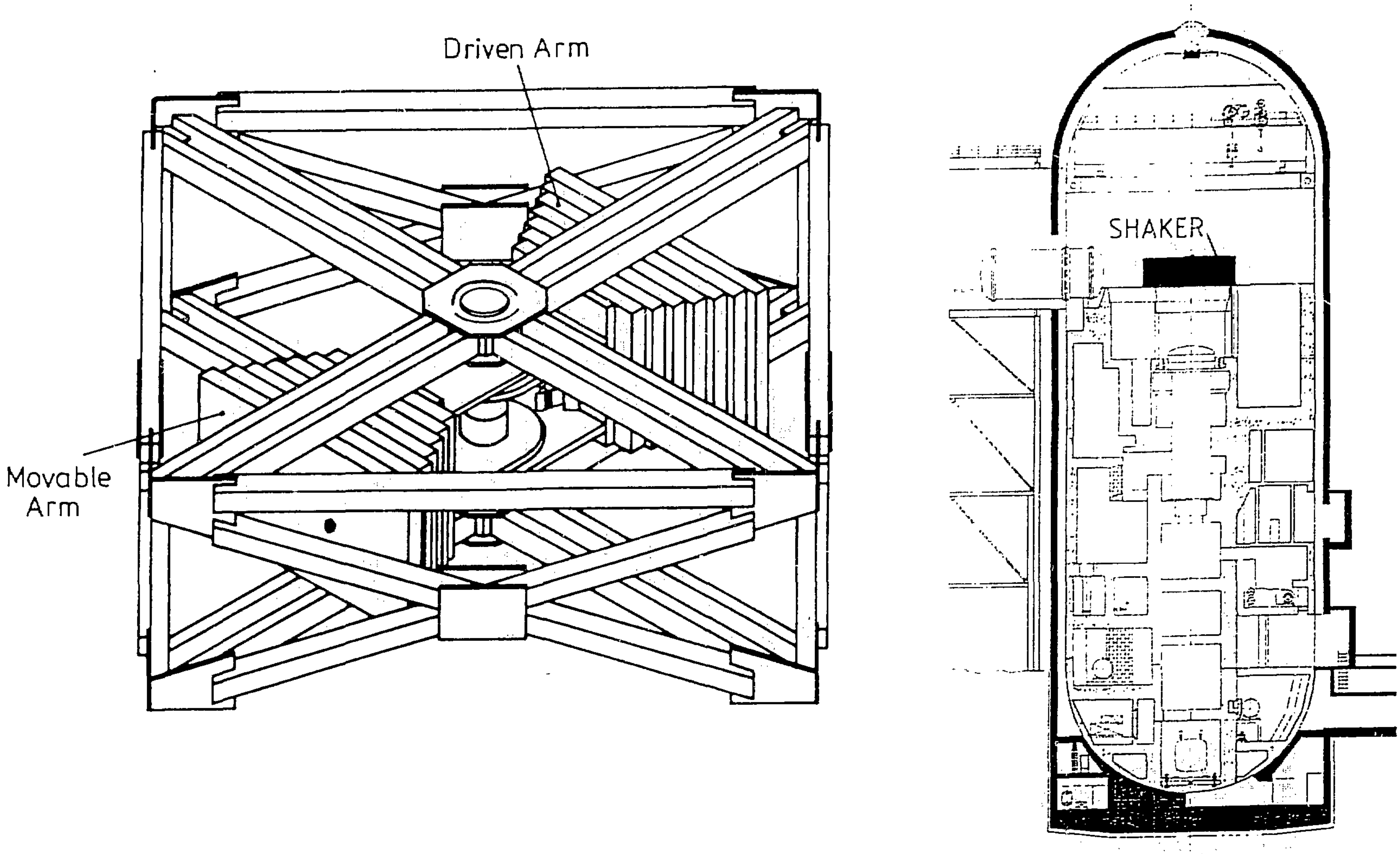


Fig. 2. ANCO MK16 Shaker (Final Design)

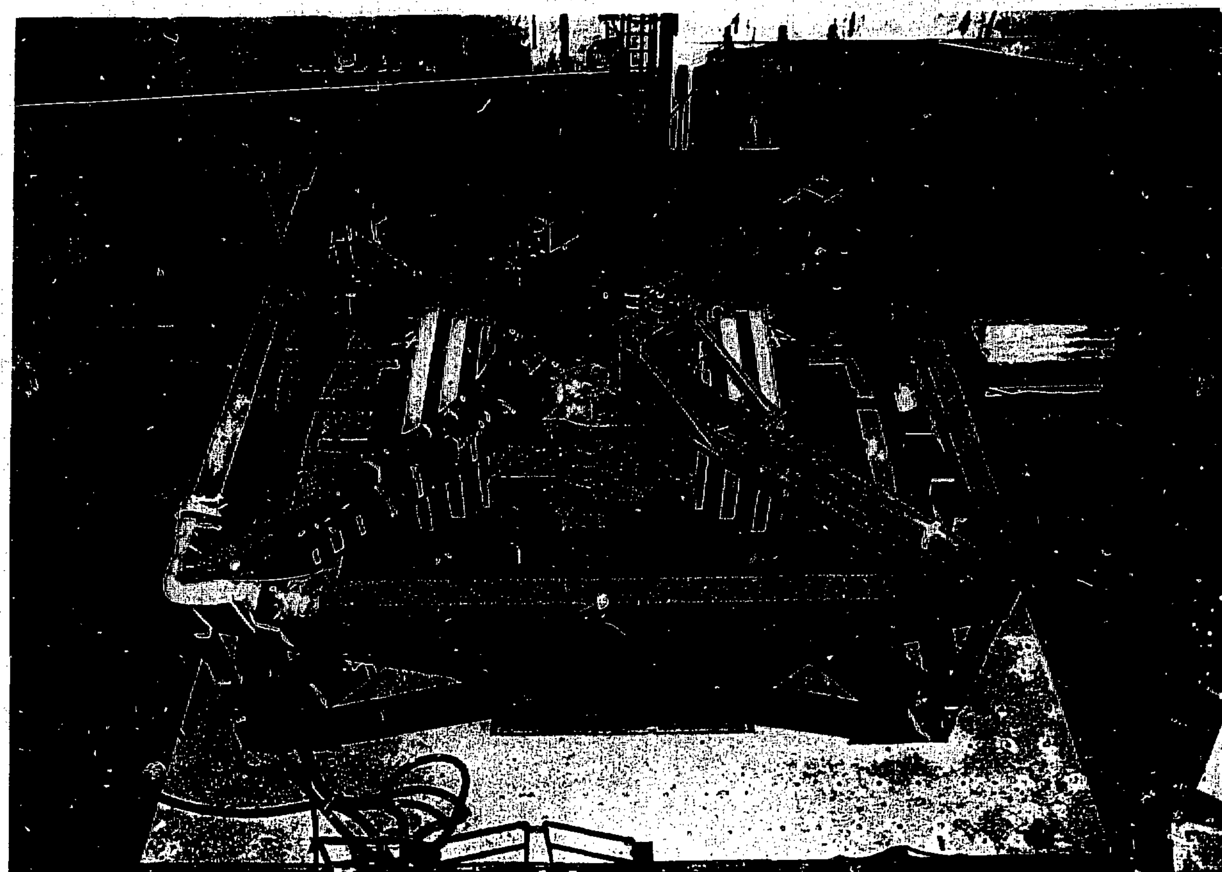

Fig. 3. Eccentric Mass Shaker in Balanced Condition

Fig. 4. Shaker Enclosure for Air Drag Reduction

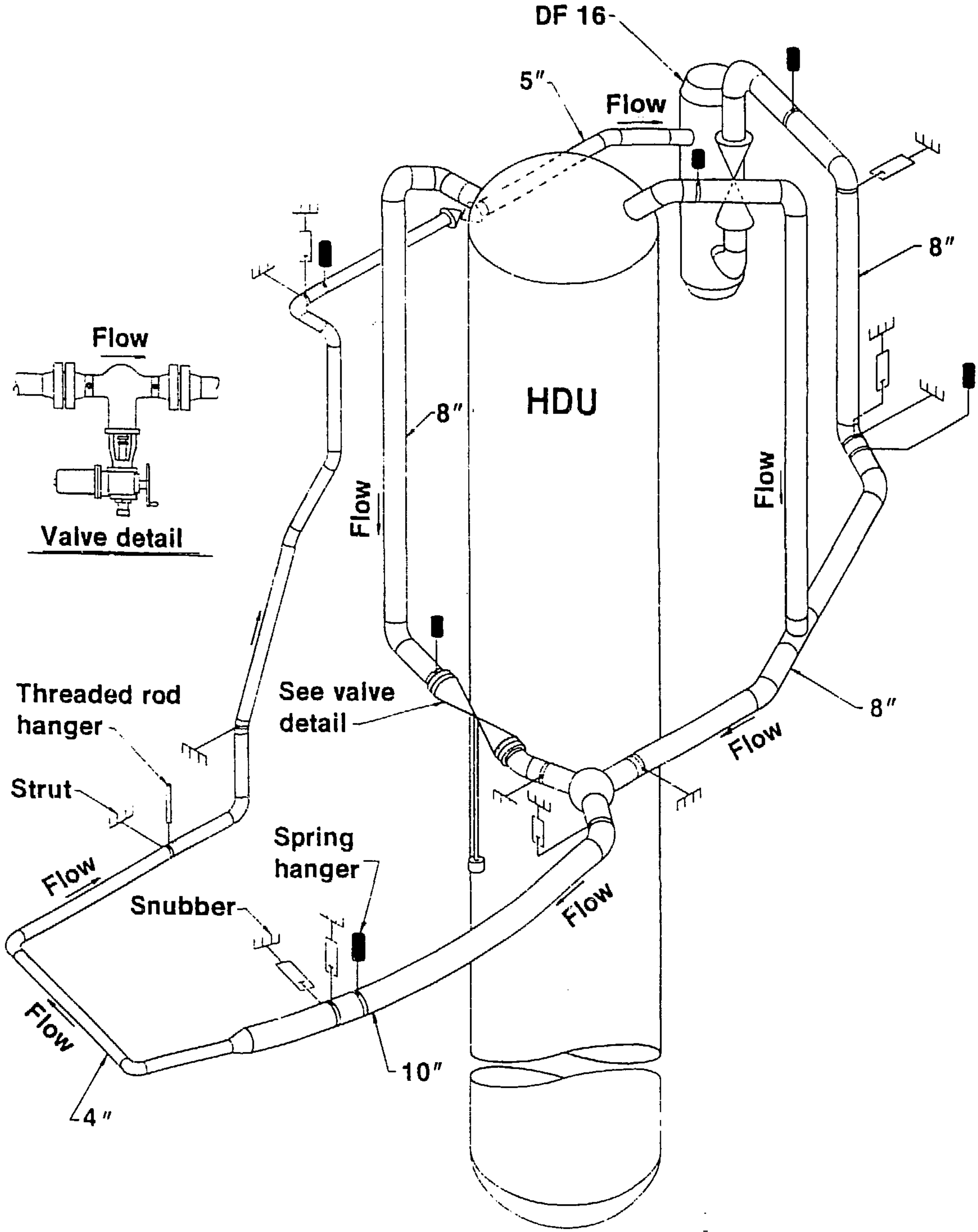


Fig. 5. VKL Piping with U.S. Rigid Support System
(Courtesy of INEL, Idaho Falls, ID)

Fig. 6. U.S. 8" Gate Valve

Fig. 7. Typical U.S. Snubber Installation

HDR T 40.
SHAG TEST MATRIX: PLANNED RUNS
2 June - 11 July 1986

| RUN NO. | TEMP. °C | VKL SUPPORT SYSTEM | ECCENTRICITY in kgm | STATRING FREQ. in Hz | MAX. FORCE in kN | TEST WEEK |
|---|---|---|---|---|---|---|
| 34 | 20 | USNRC | 4000 | 6 | 5600 | 1 |
| 35 | 20 | USNRC | 4000 | 8 | 10100 | |
| 36 | 20 | USNRC | 8200 | 5.6 | 10100 | |
| 37 | 20 | USNRC | 27800 | 2.1 | 4800 | |
| 32 | 20 | USNRC | 16800 | 4 | 10600 | 2 |
| 42 | 20 | EPRI/EA | 16800 | 4 | 10600 | |
| 52 | 20 | EPRI/SS | 16800 | 4 | 10600 | |
| 12 | 20 | HDR | 16800 | 4 | 10600 | |
| 22 | 20 | KWU | 16800 | 4 | 10600 | |
| 21 | 210 | KWU | 8200 | 5.6 | 10100 | 3 |
| 11 | 210 | HDR | 8200 | 5.6 | 10100 | |
| 51 | 210 | EPRI/EA | 8200 | 5.6 | 10100 | |
| 41 | 210 | EPRI/SS | 8200 | 5.6 | 10100 | |
| 31 | 210 | USNRC | 8200 | 5.6 | 10100 | |
| 30 | 210 | USNRC | 4000 | 8 | 10100 | 4 |
| 40 | 210 | EPRI/EA | 4000 | 8 | 10100 | |
| 50 | 210 | EPRI/SS | 4000 | 8 | 10100 | |
| 10 | 210 | HDR | 4000 | 8 | 10100 | |
| 20 | 210 | KWU | 4000 | 8 | 10100 | |
| 23 | 20 | KWU | 60000 | 2.1 | 10400 | 5 |
| 13 | 20 | HDR | 60000 | 2.1 | 10400 | |
| 33 | 20 | USNRC | 60000 | 2.1 | 10400 | |
| 43 | 20 | EPRI/NA | 60000 | 2.1 | 10400 | |
| 53 | 20 | EPRI/SS | 60000 | 2.1 | 10400 | |
| 58 | 20 | EPRI/SS | 27800 | 3.1 | 10500 | 6 |
| 48 | 20 | EPRI/EA | 27800 | 3.1 | 10500 | |
| 19 | 20 | HDR | 101800 | 1.6 | 10200 | |

Fig. 8. SHAG Test Matrix - Planned

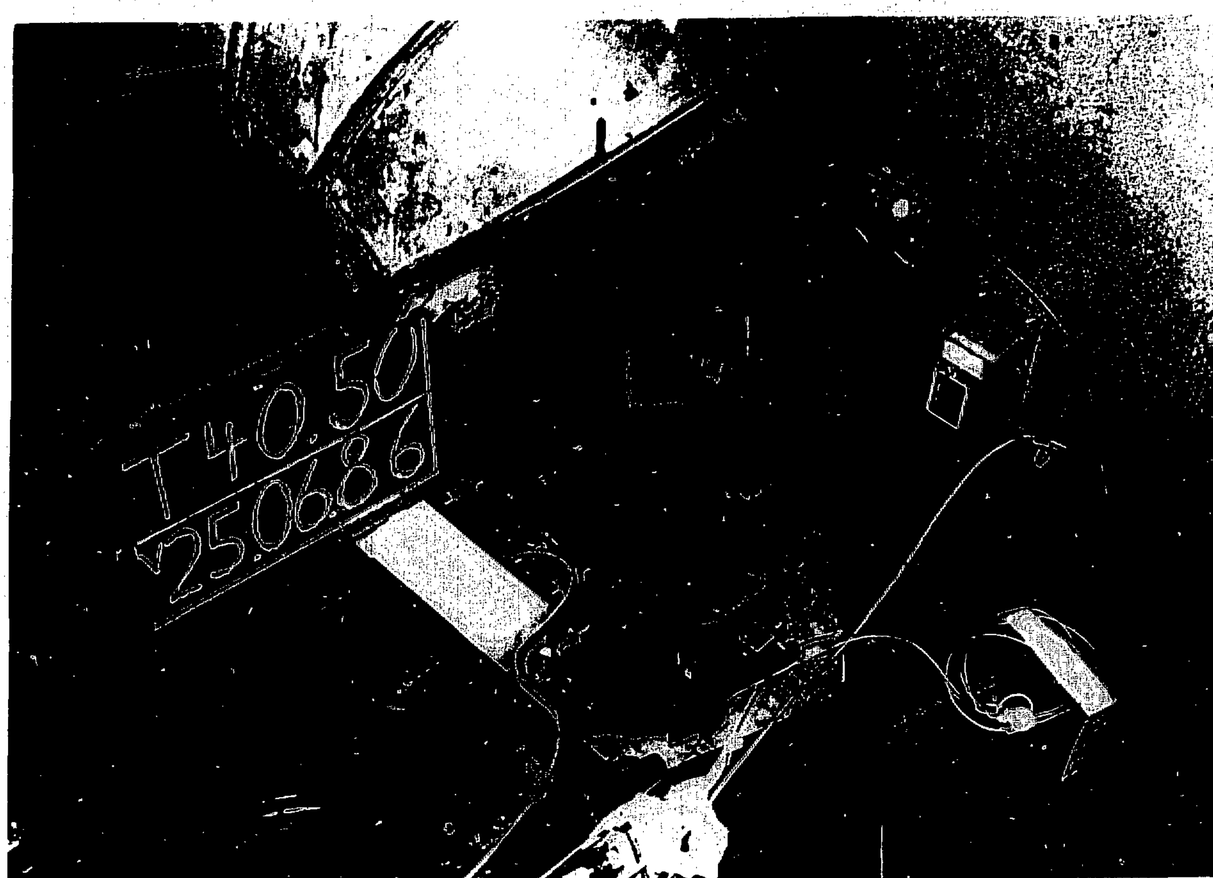


Fig. 9. Wall Accelerometer Measuring Input to VKL Piping Support

HDR T 40.
SHAG TEST MATRIX: RUNS PERFORMED
2 June - 22 July 1986

| RUN NO. | TEMP. °C | VKL SUPPORT SYSTEM | ECCENTRICITY in kgm | STATRING FREQ. in Hz | MAX. FORCE in kN | TEST WEEK |
|---|---|---|---|---|---|---|
| 34 | 20 | USNRC | 4700 | 6 | 6600 | |
| 35 | 20 | USNRC | 4700 | 8 | 11800 | 1 |
| 36 | 20 | USNRC | 8200 | 5.6 | 10100 | |
| 37 | 20 | USNRC | 27800 | 2.1 | 4800 | |
| 40 | 20 | EPRI/EA | 4700 | 8 | 11800 | |
| 20 | 20 | KWU | 4700 | 8 | 11800 | 2 |
| 60 | 20 | GERB | 4700 | 8 | 11800 | |
| | | | | | | 3 |
| 50 | 20 | EPRI/SS | 4700 | 8 | 11800 | |
| 70 | 20 | ANCO | 4700 | 8 | 11800 | 4 |
| 10 | 20 | HDR | 4700 | 8 | 11800 | |
| 30 | 20 | USNRC | 4700 | 8 | 11800 | |
| 31 | 20 | USNRC | 6450 | 6 | 9100 | |
| 41 | 20 | EPRI/EA | 6450 | 6 | 9100 | |
| 21 | 20 | KWU | 6450 | 6 | 9100 | 5 |
| 11 | 20 | HDR | 6450 | 6 | 9100 | |
| 51 | 20 | EPRI/SS | 6450 | 6 | 9100 | |
| 52 | 210 | EPRI/SS | 8200 | 4.5 | 6500 | |
| 32 | 210 | USNRC | 8200 | 4.5 | 6500 | |
| 42 | 210 | EPRI/EA | 8200 | 4.5 | 6500 | 6 |
| 12 | 210 | HDR | 8200 | 4.5 | 6500 | |
| 22 | 210 | KWU | 8200 | 4.5 | 6500 | |
| 12.1 | 210 | HDR | 8200 | 4.5 | 6500 | 7 |
| 14 | 20 | HDR | 33000 | 1.6 | 3300 | |
| 16 | 20 | HDR | 54000 | 1.6 | 5400 | 8 |
| 13 | 20 | HDR | 67000 | 1.6 | 6700 | |

Fig. 10. SHAG Test Matrix - Performed

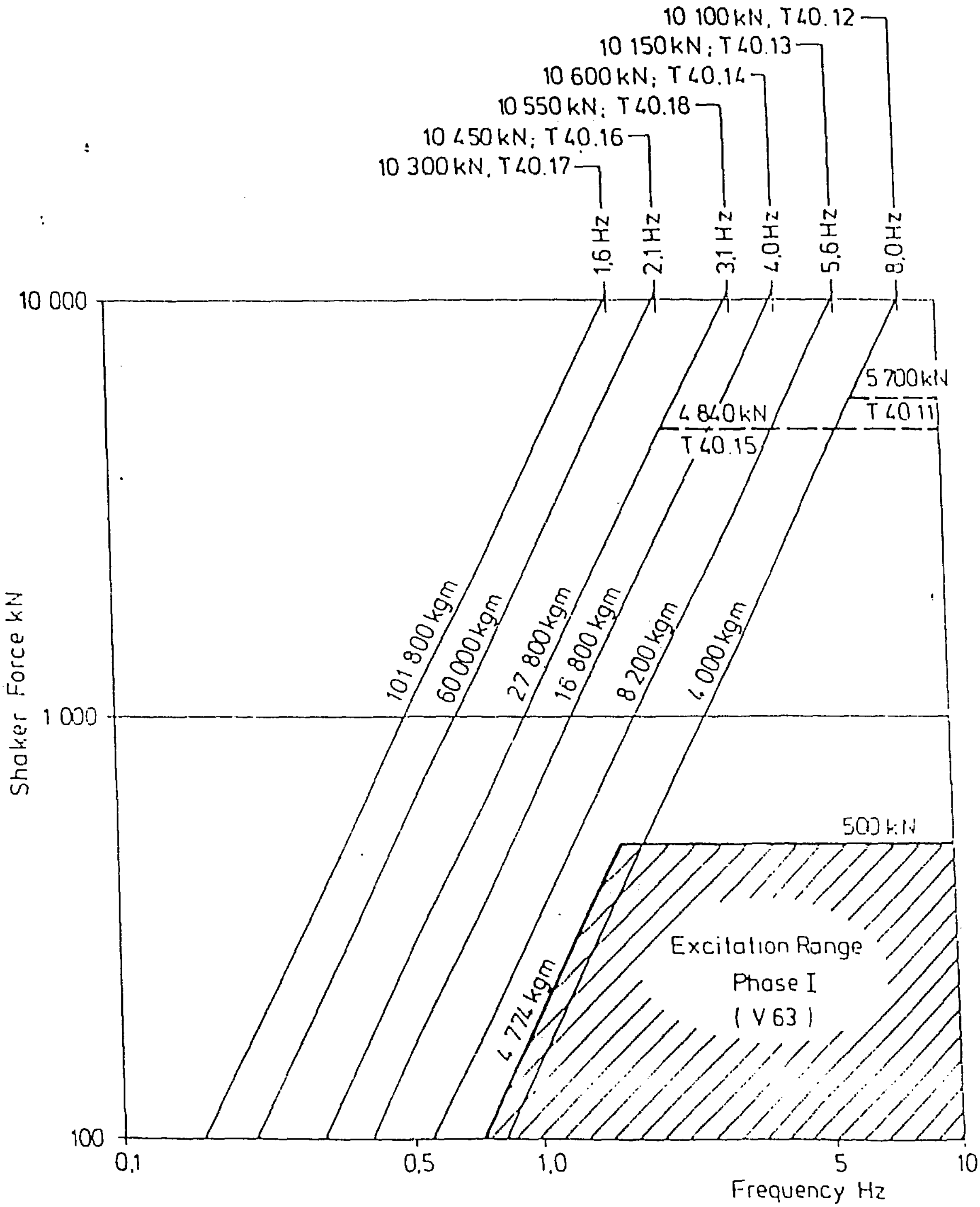


Fig. 11. Planned and Actual Force-Frequency Region for SHAG Experiments